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This is the final report on ONR Contract number N00014-85-K-0113, NR 150-535, Calibration of Test Items and Measurement of Abilities. The report reviews the results obtained during the period January 1985 through September 1988. The results include the development of a general Bayesian framework for item response analysis and Bayesian estimation of item and ability parameters. A listing of technical reports and publications resulting from the contract is also presented.

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Calibration of Test Item and Measurement of Abilities

by

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Introduction

The overall goal of this project is to develop new Bayesian procedures for mental testing. A typical test, which is studied here, consist of k test items administered to n examinees. The data consists of an nxk matrix of binary responses indicting which of the k items are scored correctly and which incorrectly by each of the n examinees.

The statistical procedures are based on the assumption that there is a model which specifies the probability of a correct response to each item as a function of an unidimensional ability. Such functions are assumed to belong to certain families such as the two-parameter logistic (2PL) or three-parameter (3PL) curves. These curves are identified by parameters called item parameters.

When these models are used for testing, a set of items is initially calibrated using a moderately large value for n (the sample size). The calibration consists of estimating the item parameters. The calibrated curves are then used to score abilities of new examinees.

It is standard practice to ignore the uncertainty in the items once the calibration is complete and to estimate abilities assuming that the item parameters are known. This practice can lead to serious inferential errors in the measurement of abilities. In particular, an interval estimate of an ability can be too narrow giving a false impression of the accuracy of the estimate.

The sequential nature of first calibrating and then scoring makes the Bayesian approach particularly appropriate. According to this approach, an analysis is made of the uncertainties in the estimated items at the calibration phase. This uncertainty is then taken into account when abilities are measured. The uncertainty in the measured ability is not only due to the randomness of responses from individuals with the same ability, but also due to the uncertainty in the calibrated items.

The Bayesian paradigm can be extended to on-line calibration, where new items are introduced with items which have already been calibrated. In this situation the uncertainties of abilities based on the calibrated items are incorporated into the uncertainties of the new items. Again the typical standard practice is to ignore the uncertainties in the abilities of individuals used for the calibration of the new items.

In order to develop this general Bayesian approach to mental testing, the research was divided into the following four topics and the results are outlined below.

I. Development a general Bayesian framework for item response analysis.

II. Estimation of item parameters.

III. Estimation of abilities.

IV. On-line calibration.

I. Bayesian Framework

The general framework for Bayesian item response theory has been described in Tsutakawa and Lin (Psychometrika, 1986). Given that the item response curves belong to a certain parametric family, a prior distribution for the item parameters are assumed. The joint likelihood function of ability and item parameters is based on the assumption of local independence. The ability are assumed iid N(0,1). The marginal likelihood function is then the average of the joint likelihood function weighted by the N(0,1) prior. The marginal likelihood function is then multiplied to the prior to get the (unnormalized) posterior for the item parameters. The marginal posterior for the ability parameter can be similarly expressed but is not easy to work with due to the multiple integrals involved.

II. Estimation of item parameters

The general approach developed for item parameter estimation is to use as point estimate the posterior mode and as measure of uncertainty the posterior covariance matrix. The use of the EM algorithm for computing the posterior mode is described in Tsutakawa and Lin (1986). A novel feature of this paper is the use of the ordered bivariate beta to form a prior distribution for the item parameters in 2PL. This paper proposes the use of the inverse posterior information matrix to approximate the posterior covariance matrix. It also illustrates the relative closeness of estimated values in repeated samples, when compared to standard methods such as LOGIST (Wingersky, Barton & Lord 1982).

In Rigdon and Tsutakawa (JES 1987) an empirical Bayes procedure is developed for the case in which both ability and item parameters are sampled from population distributions with unknown hyperparameters. Here the EM algorithm (Dempster, Laird, & Rubin, JRSS-B 1977) is modified to simultaneously estimate the hyperparameters. Simulations are used to show the robustness of this approach relative to marginal maximum likelihood in the case of the Rasch model.

The use of the Dirichlet distribution to form a prior distribution for item parameters in 3PL is studied in Tsutakawa (TR143, 1988). The conventional Bayesian approach assume prior independence of parameters within items. This paper suggests a simple device to represent the prior dependence among parameters within items. The emphasis here is on looking at curves rather than parameters. Bayesian modal estimates are compared with LOGIST (Wingersky, Barton, and Lord, 1982) and marginal maximum likelihood. The robustness of the Bayesian estimate relative to weights placed on the prior is also illustrated. One notable feature of the Bayesian method is that there are much fewer outliers with unreasonable values.

III Ability estimation

Bayesian approximations to the posterior mean and variance of ability are proposed and illustrated for 2PL in Tsutakawa and Soltys (JES, 1988). The standard empirical Bayes approximations are posterior moments conditional on assuming the unknown item parameters to equal those estimated at the calibration phase. The new approximation modifies this by adding terms representing, and correcting for, the uncertainties of the calibrated item parameters. It is a special case of Lindley's (1980) approximation when the 3rd partial derivatives of the logposterior vanish. The new approximation shows that the empirical Bayes approximation consistently underestimates the posterior variance. Other approximations, including those by Leonard (1982) and Tierney and Kadane (1986), have also been examined and found to require an excessive amount of computing and therefore not suitable for routine use in ability estimation.

The Bayesian approximation was then extended to 3PL in Tsutakawa and Johnson (TR147, 1988). This paper demonstrates that maximum likelihood and empirical Bayes, both of which replace unknown item parameters by those estimated, grossly underestimate the variance of the ability parameters. The numerical examples, upon which much of the conclusion is reached, is based on a sample of n=400. Although the discrepancies between the procedures should decrease as n increases, there is some feeling at even at n=1600 the differences might not be negligible.

IV On-line calibration

Work on this topic remains incomplete due to the delay encountered in developing computer programs for Bayesian ability estimation under 3PL. The delay was due to untimely personnel changes, which required finding and training a new computer programmer each time a person left.

Summary

The development of Bayesian item response theory requires considerable amount of computation and new techniques for approximating posterior distributions. This research demonstrates that computational problems (though far from solved) can be dealt with by careful use of asymptotic approximations. It also demonstrates that reasonable prior distributions can be formulated in spite of the complexities of IRT models. But more importantly it shows the feasibility of developing a comprehensive and complete theory which can be adapted to large scale testing environments.

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